SURFACE MICROMACHINED MECHANICAL MICROPUMPS AND FLUID SHEAR MIXING, LYSING, AND SEPARATION MICROSYSTEMS

CROSS REFERENCE TO RELATED APPLICATIONS

This application claims the benefit of U.S. Provisional Application No. 60/422,548 entitled "SURFACE MICROMACHINED MICROPUMPS AND FLUID SHEAR MIXING, LYSING, AND SEPARATION MICROSYSTEMS", filed on October 31, 2002, which is incorporated by reference into the current application in its entirety.

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

Development for this invention was supported in part by U.S. Department of Energy Contract No. DE-AO385. Accordingly, the United States Government may have certain rights in this invention.

FIELD OF THE INVENTION

The invention is directed generally to micromachined mechanical devices, and more particularly, to micromachined pumps capable of pumping fluids at micro and nano scales and related shear driven mixing, lysing, and separation devices.

BACKGROUND

Miniature pumps, hereafter referred to as micropumps, are in great demand for environmental, biomedical, medical, biotechnical, printing, analytical instrumentation, and miniature cooling applications. Other typical applications include use of micropumps in

drug delivery systems, including both transdermal and impantable systems, micro total analysis systems, and electronic cooling devices. Just as in lager-scale applications, various pump designs are required for different micropump systems. For certain applications in which space is at a premium and in which fluid volumes are small, pumps with minimal dimensions, particularly pump cavity dimensions, are of interest.

Currently available micropumps typically are fabricated using etched silicon or glass substrates that are bonded together and utilize an actuation mechanism that most often is a piezo-electric bimorph, or in the case of electrokinetic micropumps, embedded electrodes. Typically, each component is individually bonded to other components to form a pump. As a result, this process is labor intensive and expensive. The resulting high price of the micropumps may preclude profitable commercialization of these micropumps. Moreover, the bonding of a plurality of components renders these pumps susceptible to reliability problems, such as separation of the bonds.

Thus, a need exists for an efficient, inexpensive micropump that is capable of being produced in mass quantities with little or no assembly required.

In addition, many fluids of interest in microfluidic applications are biological or contain complex chemical mixtures. Such solutions often must be analyzed or manipulated to separate a constituent of interest or to mix in chemical reagents. Because the flow in microfluidic devices essentially is laminar having a low Reynolds number, it is difficult to complete these tasks using the turbulence and inertia based methods effective at larger scales.

Also, in certain applications it can be necessary to lyse cells in order to access cellular constituents (e.g. DNA or RNA). Typically, cell lysis is accomplished using a centrifuge or

sonication in a bead solution. However, neither method is readily scaleable to microdevices. Therefore, a need exists for microfluidic cell lysis, mixing and separation devices.

SUMMARY OF THE INVENTION

This invention is directed to micropumps formed from monolithic structures having thicknesses of no more than about 12 microns and include pumping chambers with inlets and outlets, and structures for mechanically urging fluid from the inlet to the outlet. The micropumps may be capable of pumping fluids on the micro and nano scales. Each of these pumps may be capable of being produced complete with the actuation and transmission mechanisms in batches of hundreds to thousands per batch using surface micromachining. Consequently, pumps according to this invention can provide increased reliability and can be produced with little, if any, costs associated with manual assembly.

Micropumps embodiments include viscous micropumps and ring gear micropumps. The viscous micropumps include spiral micropumps, centrifugal micropumps, and micropumps without spiral protrusions, which are referred to as Von Karman micropumps. The ring gear micropumps include crescent micropumps and planetary gear micropumps.

According to one aspect of this invention, a micropump, referred to as a spiral micropump, includes a rotatable disk and a stationary plate. A spiral protrusion is attached to the rotatable disk and draws a fluid through an inlet port in the micropump. The fluid passes through a spiral channel formed by the spiral protrusion and between the rotatable disk and stationary plate. The fluid is expelled through an outlet port. The rotatable disk and stationary plate may be sealed with a variety of seals, which may include, but are not limited to, a seal resembling a labyrinth or a housing.

In another embodiment of this invention, a micropump is configured identically to the spiral micropump, but does not include the spiral protrusion. This micropump is referred to as the Von-Karman pump and operates using the viscous drag that develops in the fluid in the micropump as the rotatable disk rotates. This embodiment is advantageous because this micropump is not limited by the small aspect ratio that characterizes surface micromachined devices.

In yet another embodiment of this invention, a micropump is configured to include a radial array of vanes attached to a gear disk that defines an impeller of the micropump. This micropump is referred to as the centrifugal micropump.

Certain pumping devices described herein can generate a shear field. Such a field can be used to lyse cells at the microscale where centrifugation and sonication are less effective. Also, by positioning different solution constituents at different streamlines in the shear field, cells can be separated and eluted at the end of the micropump according to their position in the shear field. Those constituents closest to the moving plate will be eluted first and those constituents closest to the stationary plate will be eluted last. This type of constituent separation can be enhanced by operating the shear pump against a pressure gradient. Methods of manipulating constituents as to their location in different layers of a varying cross-stream shear field include but are not limited to: electrical fields (AC and DC), hydrodynamic forces, sedimentation forces, thermal gradients and diffusion.

Other embodiments of this invention include ring gear micropumps. One type of ring gear micropump is a crescent micropump that is formed from a ring gear having a plurality of teeth on its inner and outer surfaces. The teeth on the inner surface are configured to mesh with an idler positioned within the inner aspects of the ring gear, and the teeth on the outer

surface are configured to mesh with teeth on a transmission gear used to drive the ring gear. The micropump includes an inlet port and an outlet port in the inner aspects of the ring gear. The crescent micropump further includes a crescent shaped component for positioning the idler and the ring gear relative to each other. The crescent micropump operates by rotating the ring gear using, for instance, a transmission gear, which in turn causes the idler to rotate. The rotating idler draws a fluid from the inlet port and expels the fluid through the outlet port.

In yet another embodiment of a ring gear micropump, the micropump, referred to as a planetary gear micropump, is composed of a ring gear having a sun gear and first and second planetary gears positioned in interior aspects of the ring gear. The ring gear has a plurality of teeth positioned on an inner surface of the ring gear that mesh with the planetary gears. The sun gear is coupled to a pivot positioned eccentrically within the sun gear, and the diameter of the first planetary gear may be larger than the diameter of the second planetary gear.

This micropump is operable by rotating the ring gear, which causes the planetary and sun gears to rotate. The eccentric pivot causes the sun gear to rotate around the pivot and oscillate. This oscillation creates successive increasing and decreasing volumes on either side of the sun gear and the first and second gears, which draws fluid into the micropump through an inlet port and expels fluid out of the micropump through an outlet port.

The various gearing systems and mechanisms of the ring gear micropumps can be used to move fluids continuously through the micropump using positive displacement. The gears may also act to lyse cells, which is also referred to as cell lysis, when a cellular solution is pumped by the gears.

An advantage of micropumps according to the invention is that the micropumps have a monolithic body. For example, these pumps may be constructed using Sandia National Laboratories' Ultraplanar Multi-level MEMS Technology (SUMMiT™) process or similar process. As the micropumps formed by this process are monolithic, the micropumps do not require additional assembly. The SUMMiT™ process uses three our four movable polysilicon layers together with one stationary polysilicon layer. The polysilicon layers are separated from adjacent layers by sacrificial oxide layers.

Another advantage of these pumps is their ability to operate in micro and nano scales.

Yet another advantage of this invention is that the micropumps can operate without valves, thereby making the micropumps more reliable and having less components as compared to micropumps having valve requirements. Furthermore, because the pump is continuous flow rather than pulsatile flow, a continuously and smoothly varying flow rate may be generated without use of microfluidic capacitors to dampen the oscillations.

These and other features and advantages of the present invention will become apparent after review of the following drawings and detailed description of the disclosed embodiments.

BRIEF DESCRIPTION OF THE DRAWINGS

The accompanying drawings, which are incorporated in and form a part of the specification, illustrate preferred embodiments of the presently disclosed invention(s) and, together with the description, disclose the principles of the invention(s). These several illustrative figures include the following:

Figure 1 is a schematic perspective illustration of a partial cutaway of a spiral micropump;

Figure 2 is an exemplary spiral micropump coupled to a typical electrostatic comb drive system for supplying rotational motion to the micropump;

Figure 3 is a cross-sectional view of the spiral micropump of Figure 2;

Figure 4 is a picture of a spiral micropump expelling a droplet of fluid under experimental conditions;

Figure 5(a) is a cross-sectional view of spiral micropump of Figure 2;

Figure 5(b) is a detail view of a portion of the spiral micropump of Figure 5(a);

Figure 6(a) is a top view of the spiral micropump of Figure 2 including a housing seal;

Figure 6(b) is a cross-sectional view taken at section line A-A in Figure 6(a);

Figure 6(c) is a cross-sectional view taken at section line B-B in Figure 6(b);

Figure 6(d) is a detail view of a portion of the spiral micropump shown in Figure 6(a);

Figure 7 is a schematic illustration of a crescent micropump;

Figure 8 is a picture of two exemplary crescent micropumps, the micropump on the left side having a top cover and the micropump on the right side without a top cover;

Figure 9 is a cross section of the crescent micropump of Figure 7;

Figure 10 is a schematic illustration of a planetary gear micropump;

Figure 11 is a collection of schematic illustrations of the micropump of Figure 10 in various orientations during operation;

Figure 12(a) is a cross-sectional top view of a Von Karman micropump;

Figure 12(b) is a cross-sectional front view of the Von Karman micropump of Figure 12(a); and

Figure 13 is a cross-sectional top view of a centrifugal micropump.

DETAILED DESCRIPTION OF THE INVENTION

This invention includes numerous embodiments of monolithic micropumps that are capable of pumping fluids and are configured for use in microelectromechanical systems (MEMSs). These micropumps are monolithic structures having thicknesses of no more than about 12 microns and include pumping chambers with inlets and outlets, and structures for mechanically urging fluid from the inlet to the outlet. As used herein, the term monolithic refers to the resulting structure obtained from an integrated circuit formation process, which generally comprises a plurality of lithography, etching, and deposition steps. Thus, no assembly steps, such as bonding steps, are needed as the various layers are inherently self-assembled. Although the micropumps according to the invention are fully monolithic, use of this term does not preclude substantially free movement of one layer relative to another layer, such as in the case of a spinning rotatable disk.

Micropumps according to the invention have a total thickness of no more than about 12 microns. Thicknesses of the micropumps described herein are less than the thicknesses of conventional piezoelectric driven membrane pumps having, which have thicknesses of between about 80 microns and about 100 microns. The relatively high efficiency of pumps having thicknesses of 12 microns or less is an unexpected result because as the thickness is reduced to no more than 12 microns, the Reynolds number decreases and the effective viscosity increases. Therefore, it would be expected that the low Reynolds number would

render pumps according to the invention ineffective. However, it has been found for thickness of no more than about 12 microns, that viscous effects actually begin aiding pumping as the mechanism for pumping is based on viscous drag and not on inertial effects.

Embodiments of these micropumps, which are described in detail below, include viscous micropumps formed from rotatable discs and ring gear micropumps. The viscous micropumps include a spiral micropump, a Von Karman micropump, which is a spiral micropump without a spiral protrusion, and a centrifugal micropump. The ring gear micropumps include a crescent micropump and a planetary gear micropump. The micropumps may be actuated electrostatically using on-chip micro-engines. Slightly larger meso-scale versions of these pumps can be fabricated using more conventional machining techniques and powered using small electric motors.

These micropumps may be used in a variety of applications. For instance, these micropumps may be included as a component of an integrated circuit system and be placed in communication with microprocessors, amplifiers, actuators, voltage controllers for the actuators, sensors and other appropriate devices. These micropumps may be used as a component in microlabs, which may also be referred to as a lab-on-a-chip, in medical devices, such as insulin pumps, chemical synthesis, for cooling systems in integrated circuits, and other applications.

Each of these embodiments is preferably formed using surface machining processes capable of fabricating hundreds or thousands of devices together with no part assembly being required. Surface micromachined devices are planar in nature, and are characterized by very shallow depths, such as, but not limited to, no more than about 12 microns. The micropumps may be fabricated using Sandia National Laboratories' Ultraplanar Multi-level MEMs

Technology (SUMMiT™) process or similar process. The SUMMiT™ process uses three or four movable polysilicon layers together with one stationary polysilicon layer ("Poly"). The polysilicon layers are separated from adjacent layers by sacrificial oxide layers that are removed during the final etch release process step. See e.g. I-C Compatible Polysilicon Surface Micromachining by J. J. Sniegowski and M. P. de Boer, Annu. Rev. Mater. Sci. 2000, 30:299-333.

1. Monolithic Viscous Micropumps

A. Spiral Micropump

One embodiment of this invention, as shown in Figure 1 and referred to hereinafter as the spiral micropump, includes a rotatable disk 12 coupled to a stationary plate 14 using a pin joint 16, which is positioned generally within the center of stationary plate 14. Rotatable disk 12 includes a spiral protrusion 21 that directs fluids from an inlet port 18 to an outlet port 20. Stationary plate 14 is a generally flat shaped component and includes two generally flat surfaces. One of these flat surfaces is positioned in close proximity to spiral protrusion 21. In one embodiment, the combined thickness of rotatable disk 12, stationary plate 14, and spiral protrusion 21 is no more than about 12 microns. In at least one embodiment, the spiral micropump may be formed from as few as 2 silicon layers. However, the sprial micropump may be formed from between 3 and 5 silicon layers as well.

In another embodiment, the micropump contains the components described above; however, spiral protrusion 21 is not included. Rather, this embodiment, which is referred to as a viscous micropump, pumps fluids using viscous phenomena as the driving mechanism.

During operation, a fluid enters inlet port 18 and flows through spiral channel 22 to outlet port 20. Spiral channel 22 is formed by spiral protrusion 21 that is bounded by stationary plate 14 on one side and rotatable disk 12 on the other side. Fluids, with or without suspended particles, are drawn through spiral channel 22 as a result of a velocity profile created by rotatable disk 12 rotating around pin joint 16. The velocity profile consists of fluids having velocities that vary between about zero at the surface of stationary plate 14 and a velocity approximately equal to the rotational velocity of the rotatable disk at a location proximate to the inner surface 24 of rotatable disk 12. Viscous stresses on upper surfaces of the spiral channel 22 allow fluids to be transported against an imposed pressure difference. The spiral micropump is capable of expelling a sufficient amount of fluids to produce droplets of fluid visible to the unassisted human eye, as shown in Figure 4.

Rotatable disk 12 may be rotated through numerous methods. In one embodiment, rotatable disk 12 is rotated using an electrostatic comb drive microengine, as shown in Figure 2, that provides continuous mechanical power transmitted to rotatable disk 12 through a transmission 26, which may be a torque amplification gear mechanism operating at 12:1. Transmission 26 includes an output gear 28 that includes a plurality of teeth positioned on a perimeter 30 of output gear 28. The teeth on output gear 28 mesh with the teeth located on the perimeter 30 of rotatable disk 12.

Figure 3 is a cross-sectional view of the spiral micropump taken through the centerline to illustrate the relationships between the layers forming the spiral micropump. Rotatable disk 12 is formed from a polysilicon layer, which is identified as Poly 4, and stationary plate 14 is formed from another polysilicon layer, which is identified as Poly 0. Spiral protrusion 21 is formed from three polysilicon layers, which are identified as Poly 1,

Poly 2, and Poly 3, and is anchored to rotatable disk 12. This configuration leaves a small gap between spiral protrusion 21 and stationary plate 14.

The spiral micropump may be contained using a variety of seals or components for preventing fluids from leaking out. In one embodiment, seal 32 resembles a labyrinth seal positioned around the periphery of the spiral micropump, as shown in Figure 5. The seal 32 can be formed from three polysilicon layers. In one embodiment, the three layers may be concentric and cylindrical. However, the layers are not limited to this shape or number. Rather, seal 32 may be formed from any other number of layers or alternative shapes.

The three layers are positioned between the rotatable disk and the fixed plate. The inner and outer layers form protrusion extending from the stationary plate 14 and Poly 0, and the middle layer forms a protrusion extending from the rotatable disk 12 and Poly 4 and positioned between the protrusions extending from the stationary plate 14. The middle layer rotates with the rotatable disk 12. A small clearance gap is located between adjacent layers. As shown in Figure 5, the three cylindrical layers are defined by interconnected layers designated as Poly 1, Poly 2, and Poly 3.

In another embodiment, as shown in Figure 6, seal 32 may be a housing that nearly entirely encloses rotatable disk 12, stationary plate 14, and spiral protrusion 21, except for a small opening through which transmission 26 contacts rotatable disk 12. Figure 6(b) is a cross-sectional view of the spiral micropump and shows seal 32 formed from a top cover 36 that is formed from a Poly 4 layer, a side wall 38 that is formed from Poly 1, Poly 2 and Poly 3 layers, and a bottom cover 40 that is formed from a Poly 0 layer. Top cover 36 and side wall 38 form a closed chamber that surrounds rotatable disk 12 and stationary plate 14. In this embodiment, spiral protrusion 21 is defined by the Poly 1 and 2 layer and is attached to

rotatable disk 12. The Poly 1 layer may also include dimples that create protrusions below the spiral protrusion 21 to improve the seal between the poly layers forming spiral protrusion 21. Seal 32 may further include a cantilever seal 42, as shown in Figure 6(d), for reducing leakage from the bottom of pumping chamber 44 through an opening. Seal 32 may also include a dimple 48, which may be formed by a dimple cut in the Poly 3 layer, for minimizing leakage from the top of pumping chamber 44 through a window.

Micropumps according to the invention may also be used to lyse cells by pumping a cellular solution at a shear rate sufficient to destroy the cell membrane. In addition, the shear field created in the spiral or viscous micropumps can be used to spatially separate constituents as the constituents are eluted from the micropump.

In operation, a liquid containing cells is introduced at the inlet 18 of the spiral or viscous micropump. As the rotatable disk 12 is turned rapidly, the solution is pumped towards outlet 20, and a shear field is developed between rotatable disk 12 and stationary plate 14 that is proportional to the velocity of the rotating disk. If the resulting shear stress induced in the cells in solution is high enough, the cell membrane of the cells will rupture, which results in lysis of the cells. After the cells rupture, the fluid stream will continue to be pumped out of spiral channel 22 through outlet 20. Cellular constituents, such as DNA and cell membrane material, may be separated while flowing through spiral channel 22, as described in detail below.

The shear field developed by a viscous micropump may be used to separate constituents in a fluid stream flowing through a channel fed by the pump. Separation of the constituents is possible due to a variation in velocity of the fluid across the fluid stream. In the simplest case, the fluid near rotatable disk 12 is moving at approximately the velocity of

the rotatable disk 12, and the fluid near the stationary plate 14 has a velocity approximately equal to zero, which is the velocity of stationary plate 14. The velocity varies linearly between zero and the moving disk velocity as the fluid stream is traversed from the stationary plate to the rotatable disk.

Because the flow field through channel 22 is essentially laminar, constituents stay in layers, or lanes, as the constituents move through the micropump. The constituents closest to rotatable disk 12 are expelled from the micropump ahead of the slower moving constituents that are located closer to stationary plate 14. Because of this phenomena, constituents are separated in space and time in an exit channel as a result of the constituents occupying different layers within the fluid flow. The separation between constituents may be increased by increasing the speed of the micropump. For best operation, different constituents should be positioned at different locations across channel 22 in the flow stream. In some cases, such a constituent configuration occurs naturally because of the shear field. Different constituents occupy different lamina because of the way the constituents respond to the shear field.

Constituents may also be positioned in different fluid lamina using other methods. For instance, an electrode or an array of electrodes can be incorporated in stationary plate 14 to apply an electric field consisting of alternating or direct current (AC or DC, respectively), to the electrode or electrodes while rotatable disk 12 is grounded. Rotatable disk 12 may be grounded through the drive mechanism. This configuration produces an electric field that is generally perpendicular to the direction of fluid flow. The solution constituents are positioned differently within the cross-stream field and are therefore, in different fluid lamina. The position of the solution constituents is dictated by the constituents' electrophoretic or dielectrophoretic properties. The electrophoretic properties determine the

DC signal response, and the dielectrophoretic properties determine the AC signal response. Constituents positioned in lamina nearest rotating disk 12, which is the ground, travel further through the micropump in a particular time period than other fluids.

Other methods of establishing cross-stream fields include sedimentation processes in which different specific gravity constituents are positioned at different locations in a cross-stream gravity field, and chemical affinity processes, whereby a wall of a micropump, whether stationary or rotating, is coated which causes chemical constituents to be adsorbed and removed from the fluids at different rates. Differences in diffusion coefficients correlating with different constituents causes some separation of constituents but also leads to broadening of the bands of eluted constituents as the fluids are expelled from the micropump, thereby reducing resolution.

These separation effects can be enhanced when the pump is operated against a pressure gradient, such as where the pressure at outlet 20 is greater than the pressure at inlet 18. This pressure gradient forces the fluids against the flow induced by rotatable disk 12. The fluid near stationary plate 14 is more affected by the pressure gradient than the fluid in streamlines located near rotatable disk 12. If the pressure gradient is sufficient, the fluid near stationary plate 14 will be pushed backward against the shear driven flow. This causes the solution constituents to be separated more widely because while the fluid near the stationary wall is pushed back towards inlet 18 by the pressure gradient, solution constituents near rotatable disk 12 are pulled in the usual flow direction.

While these processes produce constituent separation, the same processes may also be used for constituent mixing. Enhanced diffusion (dispersion) in the shear field occurs when the constituent concentration gradient across the stream due to along stream convection

reduces the mixing time required. Another method of mixing constituents is to stop the flow at outlet 20. In this embodiment, a re-circulation system is established in which the fluids first travel through the micropump in the forward direction along rotatable disk 12 and then travel back along stationary plate 14 due to the pressure driven flow in the low velocity streamlines positioned closely to stationary plate 14. This re-circulation region is an effective microfluidic mixer.

B. Von Karman Micropump

In another embodiment of this invention, a micropump, which is referred to as a Von Karman micropump is shown in Figures 12a and 12b. The Von Karman micropump is composed of a rotatable plate 82 that rotates on top of a parallel fixed plate 84 about pin joint 85. A cavity 86 is formed between the disk 82 and the plate 84 and for pumping the fluid. The fixed plate 84 has an inlet port 88 and an outlet port (not shown). The viscous forces caused by the rotating flat disk 82 carry the fluid from the inlet port 88 to the outlet port.

Figure 12b illustrates a Von Karman micropump that may be formed using the SUMMiT-V™ process and may have a thickness no more than about 12 microns. In at least one embodiment, the Von Karman micropump may be formed from as few as 2 silicon layers. However, the Von Karman micropump may be formed from between 3 and 5 silicon layers as well. The fixed plate 84 may be formed in Poly 0 and the inlet port 88 and may be created by a Bosch etch through the wafer. The rotatable plate 82 may be formed in the Poly 3 and may create a cavity 86 whereby the rotatable plate 82 is about six microns from the fixed plate 84. The rotatable plate 82 may be driven using gear teeth on the outer surface of the rotatable plate 82. The Poly 4 layer may form a top cover 90 that may be connected

seamlessly to the housing walls 92, which may be anchored to the ground. The housing walls 92 and the Poly 4 top cover 90 provide a continuous seal around the entire micropump, except for the area proximate to the driving gears 94. Surface tension forces prevent the fluid in the micropump from leaking through the very small gap proximate to the drive gears 94.

C. Centrifugal Micropump

Figure 13 shows yet another embodiment of a viscous drag micropump and is referred to as a centrifugal micropump. The centrifugal micropump may have a thickness no more than about 12 microns. In at least one embodiment, the centrifugal micropump may be formed from as few as 2 silicon layers. However, the centrifugal micropump may be formed from between 3 and 5 silicon layers as well. The configuration of the centrifugal micropump resembles the spiral micropump; however, the centrifugal micropump does not include a spiral protrusion. Rather, the centrifugal micropump includes a radial array of vanes 96 attached to a rotatable disk 98. The rotatable disk 98 functions as an impeller of the centrifugal micropump.

2. Monolithic Ring Gear Micropumps

A. Crescent Micropump

The invention also includes planar gear pumps, such as the crescent micropump and the planetary gear micropump, for pumping fluids and for lysing cells. The planar gear micropumps may have thicknesses no more than about 12 microns. In at least one embodiment, the planar gear micropump may be formed from as few as 2 silicon layers.

However, the planary gear micropump may be formed from between 3 and 5 silicon layers as well. The planar gears may be used to lyse cells, as described in detail above, by pumping a cellular solution through the micropump. The crescent micropump, as shown in Figure 7, includes a ring gear 48 having a plurality of teeth on its outer and inner surfaces. In at least one embodiment, the ring gear 48 may be formed from three or four layers of silicon and a base layer 49 may be formed from one or more layers of silicon. The teeth on the outer surface mesh with teeth on a drive gear, and the teeth on the inner surface mesh with an idler 52. In this configuration, a drive gear rotates and causes ring gear 48 to rotate, which in turn causes idler 52 to rotate. This action causes a fluid to be drawn into interior aspects of ring gear 48 from inlet 54 and expelled through outlet 56. Idler 52 and ring gear 50 are kept in position with a crescent diverter 58.

Figure 8 depicts two crescent micropumps 51 and 53, micropump 51 having a top cover in place and micropump 55 having the top cover removed. The crescent micropumps can be driven with torsional ratchet actuators 60, or other structure for providing rotational motion to micropumps. Torsional ratchet actuators are independently attached to transmissions 62 for applying rotational motion to ring gears 48. The crescent micropump on the right may have a cover installed using a post fabrication technique such as, but not limited to, anodic bonding.

Figure 9 depicts a cross-section of ring gear 48 including a seal 64 positioned around pumping chamber 66, which is formed as an integral part of ring gear 48. Seal 64 resembles a labyrinth seal and is formed from a dimple in the Poly 1 layer. In addition, seal 64 includes a plurality of rollers that are created using a pin joint process and act as axial bearings that support the walls of the seal during rotation and thus minimize friction.

B. Planetary Gear Micropump

Yet another embodiment of this invention, as shown in Figure 10 and referred to hereinafter as a planetary gear micropump, may be used to pump fluids or lyse cells. The planetary gear micropump may have a thickness no more than about 12 microns. In at least one embodiment, the planetary gear micropump may be formed from as few as 2 silicon layers. However, the planetary gear micropump may be formed from between 3 and 5 silicon layers as well. The micropump includes a ring gear 68 mechanically coupled to a sun gear 70 using first and second planetary gears, 72 and 74 respectively. Sun gear 70 pivots eccentrically around pivot 76 that is not in the center point of sun gear 70. Ring gear 68 drives the rotation of first and second planetary gears 72 and 74 and sun gear 70. The diameter of the first planetary gear 72 is larger than the diameter of the second planetary gear 74, or vice versa, and the sum of the diameters of sun gear 70 and first and second planetary gears 72 and 74 is approximately equal to the pitch diameter of ring gear 68. The ring gear 68 may be formed from three or more layers of silicon. A base layer may be formed from one or more layers of silicon.

Operation of the planetary gear micropump is shown in Figure 11. As ring gear 68 rotates, first and second planetary gears 72 and 74 rotate around sun gear 70. Rotation of first and second planetary gears 72 and 74 around sun gear 70 causes sun gear 70 to rotate because the gap 78 between the right side of sun gear 70 and the inner wall of ring gear 68 is smaller than the gap 80 between the left side of sun gear 70 and the inner wall of ring gear 68. As sun gear 70 rotates around pivot 76, gap 78 continues to shrink in size and sun gear is forced to make a full revolution around pivot 76. This eccentric rotation of sun gear 70

produces successive increasing and decreasing volumes on either side of sun gear 70 and the first and second gears 72 and 74. Such action provides pumping action necessary for the pump to operate.

The foregoing is provided for purposes of illustrating, explaining, and describing embodiments of this invention. Modifications and adaptations to these embodiments will be apparent to those skilled in the art and may be made without departing from the scope or spirit of this invention.